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# **FINAL REPORT**

NASA-AMES UNIVERSITY CONSORTIUM GRANT

NCC 2-5199

"ORION NEBULA AND PLANETARY NEBULAE"

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## 1. INTRODUCTION

This report summarizes the research performed at Rice University related to NASA-Ames University consortium grant NCC 2-5199 during the two year period 1996 September 1 through 1998 August 31. The research program, titled *Orion Nebula and Planetary Nebulae*, involved the analysis of *Hubble Space Telescope* (HST) imagery and spectroscopy of the Orion Nebula and of the planetary nebulae NGC 6818 and NGC 6210. In addition, we analyzed infrared spectra of the Orion Nebula taken with the *Infrared Space Observatory* (ISO). The primary collaborators at NASA-Ames were Drs. R. H. Rubin, A. G. C. M. Tielens, S. W. J. Colgan, and S. D. Lord (Tielens & Lord has since changed institutions). Other collaborators include Drs. P. G. Martin (CITA, Toronto), G. J. Ferland (U. KY), J. A. Baldwin (CTIO, Chile), J. J. Hester (ASU), D. K. Walter (SCSU), and P. Harrington (U. MD).

In addition to the Principal Investigator, Professor Reginald J. Dufour of the Department of Space Physics & Astronomy, the research also involved two students, Mr. Matthew Browning and Mr. Brent Buckalew. Mr. Browning will be graduating from Rice in 1999 May with a B.A. degree in Physics and Mr. Buckalew continues as a graduate student in our department, having recently received a NASA GSRP research fellowship (sponsored by Ames).

The collaboration was very productive, with two refereed papers already appearing in the literature, several others in preparation, numerous meeting presentations and two press releases. Some of our research accomplishments are highlighted below. Attached to the report are copies of the two major publications. Note that this research continues to date and related extensions of it recently has been awarded time with the HST for 1999-2000.

## 2. THE ORION NEBULA

Our research on the Orion Nebula, the nearest and brightest Galactic H II region primarily involved UV-optical-IR spectroscopy with HST and ISO. The HST observations involved use of the Goddard High Resolution Spectrograph and Faint Object Spectrograph to perform the first study of the UV NII] emission lines at 2143 Å & 2140 Å in a Galactic H II region. From measurements of these and other UV-optical lines, coupled with detailed photoionization models of the nebula, we found that the gas-phase value of N/O is in the range 0.13 to 0.18, a value somewhat higher than solar. Moreover, requiring that  $N^+/O^+$  be the same as the values derived solely from UV and optical lines independently, allowed a new value for the rms temperature fluctuation parameter ( $t^2$ ) to be derived in the Orion Nebula. The results were published in the 1998 March 10 issue of *The Astrophysical Journal* (copy attached). They were also discussed in invited presentations by Rubin at the *Sixth Texas-Mexico Conference on Astrophysics* held in Houston during 1997 March and by Dufour at the *Chemical Evolution from Zero to High Redshift* meeting in Garching, Germany, during 1999 October. The results have(will) appeared in meeting conference proceedings (e.g., Rubin et al. 1998, *RMAA, Serie de Conferencias*, volumen 7, pp. 34-71).

In addition, we successfully accomplished the first measurements of the infrared He I Br $\alpha$  line in the Orion Nebula (or in any H II region for that matter), with the SWS on the ISO spacecraft and used it to derive the  $He^+/H^+$  in this nebula. By comparing it to measurements of the nearby H I Br $\alpha$  line, we derived a value of  $He^+/H^+ = 0.085 \pm 0.003$ . This value is similar to values found in recent optical studies of Orion, but our technique is less affected by extinction by dust in and around the nebula. These results were published in the 1998 July 10 issue of *Astrophysical Journal Letters* (copy attached).

### 3. PLANETARY NEBULAE

We successfully obtained imagery observations of two planetary nebulae, NGC 6210 & NGC 6818, with the WFPC2 CCD camera on HST during 1997. Dufour and undergraduate student M. Browning of Rice processed the imagery of NGC 6818 during the summer of 1997 to produce calibrated maps of the nebula in the emission of [O III] 4363 Å & 5007 Å, along with H $\beta$  and H $\alpha$ , at a spatial resolution of about 0.1 arc seconds (about ten times higher than possible with ground-based telescopes). The H $\beta$  and H $\alpha$  images were ratioed to produce a map of the extinction by dust across NGC 6818, which was then used to correct the map of the observed ratio of the [O III] 5007/4363 Å line ratio, then derive point-to-point values of the electron temperature,  $T_e$ , across the nebula. This enabled us to study the spatial variations in  $T_e$  and the temperature fluctuations in the nebula. In collaboration with R. Rubin at Ames and P. Harrington at the Univ. of Maryland, we used these data to derive a rms temperature fluctuation value for the nebula. We also found that the  $T_e$  variations were irregular across the nebula and did not correlate with surface brightness or morphology. The results were presented in a poster ("HST Imagery and Temperature Fluctuations for the PN NGC 6818," by Rubin, Dufour, Browning, and Harrington) at the 1998 January meeting of the American Astronomical Society in San Diego (abstract published in *BAAS*, 30, 896, 1998).


In addition to the above quantitative mapping of the spatial variations of extinction and temperature across NGC 6818, we also constructed color-coded "false-color" images of NGC 6818 which were subsequently posted in the "Gallery of Planetary Nebulae" at the website of the Space Telescope Science Institute (<http://www.stsci.edu>). During 1998 April Dufour visited NASA-Ames to give a colloquium and work with R. Rubin on our processed data on NGC 6818 and newer imagery of NGC 6210. Subsequently Rubin and his summer student, C. Ortiz, refined the analysis of NGC 6210 to produce some rather striking color-coded images of the more complex planetary nebula NGC 6210, which led to it being called "The Turtle," and the pictures released by STScI in a press release (STScI-PR98-36, <http://opposite.stsci.edu/pubinfo/pr/1998/11/>) that was subsequently reported by several print and electronic media. Currently, we are working on modeling these two nebula and preparing a detailed analysis of their physical conditions and morphology for publication in 1999.

### 4. SUMMARY

This has been a very productive collaboration, as evident by the numerous publications and presentations, more of which will be forthcoming beyond the two years of the consortium grant. Recently, we have extended our collaborations to include Wolf-Rayet galaxies and the planetary nebula, NGC 7009, and expect that new agency funding will be forthcoming in 1999 to assist our research efforts in these nebular fields. No inventions or patents were reported on this grant.

### 5. ATTACHMENTS

(see next pages)



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# THE $\text{He}^+/\text{H}^+$ ABUNDANCE IN THE ORION NEBULA FROM INFRARED SPACE OBSERVATORY MEASUREMENTS<sup>1</sup>

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## ABSTRACT

Using the Short Wavelength Spectrometer on the *Infrared Space Observatory*, we measured in the Orion Nebula several components of the He I Br $\alpha$  transition, the first detections to the best of our knowledge in an H II region, and the H I Br $\alpha$  line. A value of  $\text{He}^+/\text{H}^+ = 0.085 \pm 0.003$  is inferred from these data and is typical of previous values found for Orion. The IR method to obtain  $\text{He}^+/\text{H}^+$  is very insensitive to extinction. The measurement of the weak He I 2.855  $\mu\text{m}$  ( $5p\ ^3P'' \rightarrow 4s\ ^3S$ ) flux permits an assessment of  $T_e$  in the He<sup>+</sup> region. Its flux relative to the flux of He I 4.0490  $\mu\text{m}$  ( $5g\ ^3G \rightarrow 4f\ ^3F''$ ,  $5g\ ^1G \rightarrow 4f\ ^1F''$  blend) is roughly  $\propto T_e$  (for  $T_e$  range applicable to most H II regions and planetary nebulae) and depends little on  $N_e$ . From our measured ratio, using  $N_e = 10^4\text{ cm}^{-3}$ ,  $T_e$  is slightly less than  $10^4\text{ K}$ . We stress that many IR measurements of a hydrogen line are likely to also include one or more significant helium line contributions. Attributing all of the flux to the stronger H I line will result in underestimates for abundance ratios relative to H<sup>+</sup>. This has usually not been taken into account in the past when deriving abundances of other ions/elements relative to H. Errors in the velocity and line width inferred may also occur by failure to consider the blended He component. Because the strongest He I lines will generally be on the blue side of their counterpart H I line, interpreting a blended feature as only H I will cause a spurious bias to lower velocities.

*Subject headings:* H II regions — ISM: abundances — ISM: atoms — ISM: individual (Orion Nebula)

## 1. INTRODUCTION

Gaseous nebulae are laboratories for understanding physical processes in all emission-line sources and are probes for stellar, galactic, and primordial nucleosynthesis. Most of the helium in the universe was produced in the big bang. The reliable determination of the primordial He abundance ( $Y_p$ ) is of fundamental interest and is certainly not a settled issue (e.g., Olive et al. 1997). Much of the emphasis on deriving  $Y_p$  is based on measurements of very low metallicity galaxies in which there is less buildup of He from galactic nucleosynthesis. While knowledge of the helium abundance in a Galactic H II region plays a minimal direct role in evaluating  $Y_p$  because of the relatively high metallicity and the need to extrapolate to zero metallicity, there are other reasons why it is important to measure an accurate He abundance. For example, here we will be testing further the theoretical predictions of the level populations for He I (Smits 1996, hereafter S96). Smits's tables of relative line emissivities from a recombination-collision-cascade model are generally the ones used in deriving He abundances from He I lines. Because of its brightness and the ability to model it with some success, the Orion Nebula is often a testbed for applying and verifying various physical processes. If some discrepancy from observations is found in Orion, it may affect the entire scale of deriving He abundances, including those used to obtain  $Y_p$ .

If H and He lines are formed by radiative recombination, then their relative intensities are  $\propto \text{He}^+/\text{H}^+$ . However, collisions from the metastable  $2\ ^3S$  level selectively enhance the intensities of some He I lines. As a result, the He abundance inferred from such lines will be systematically overestimated unless this is properly taken into account. Kingdon & Ferland (1995, 1996)

examined some of these transitions in terms of both collisional effects and self-absorption, suggesting a line-by-line modification to the dominant physics included in S96. Also, Osterbrock, Tran, & Veilleux (1992) indicated that these effects are not large for Orion.

The main purpose of this Letter is to present our new *Infrared Space Observatory* (ISO) measurements of key H and He lines. We use these to infer a  $\text{He}^+/\text{H}^+$  abundance ratio. By comparing with earlier  $\text{He}^+/\text{H}^+$  results in Orion, we will consider whether we understand the mechanisms for populating the relevant atomic levels that govern the IR He I emission addressed. We present the basic atomic physics in § 2 and the ISO observations and data reduction techniques in § 3. Our results and conclusions are discussed in § 4.

## 2. ATOMIC PHYSICS BACKGROUND

At high principal quantum number  $n$ , lines produced by angular momentum splitting, measured by quantum number  $l$ , blend. At radio wavelengths, recombination lines of H and He are adjacent each other in close proximity (e.g., tables in Towle, Feldman, & Watson 1996; Lilley & Palmer 1968). The difference in energy between H and He is then essentially determined by the different Rydberg constants  $R_H$  and  $R_{He}$ . As  $n$  becomes smaller, the  $l$ -splitting is relatively more important. He I has both a singlet and triplet ladder. With  $0 \leq l \leq n-1$  and the selection rule  $\Delta l = \pm 1$ , there are  $4n-2$  components, where  $n$  is the lower level quantum number. Thus, for the He I Br $\alpha$  transition ( $n = 5-4$ ), the splitting of the  $n = 4$  and 5 levels gives rise to a set of 14 lines. These energy levels and lines are shown in Table 1. Several of the individual He components can be distinguished from H I Br $\alpha$  with the spectral resolution of ISO.

## 3. ISO OBSERVATIONS

Spectra were obtained with the Short Wavelength Spectrometer (SWS) in SWS02 grating mode in 35 bandpasses (some overlapped in wavelength coverage) on 1997 October 12 (UT).

<sup>1</sup> Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the UK), and with the participation of ISAS and NASA.

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TABLE I  
He AND H Br $\alpha$  TRANSITIONS

$\lambda_{\text{vac}}$ ( $\mu\text{m}$ )	Transition (Upper-Lower)	Relative Intensity Theory <sup>a</sup>	Observed <sup>b</sup>	Flux <sup>c</sup> ( $10^{-18}$ W cm $^{-2}$ )
2.855020	5p $^1P^{\circ}$ -4s $^1S$	0.001714	6	$0.0719 \pm 0.0153$
3.330851	5p $^1P^{\circ}$ -4s $^1S$	$9.264E-4$	No	
3.703571	5d $^1D$ -4p $^1P^{\circ}$	0.005595	No	
4.0063997	5p $^1P^{\circ}$ -4d $^1D$	$4.287E-4$	No	
4.0377351	5f $^1F^{\circ}$ -4d $^1D$	0.02739	12	$1.11 \pm 0.134$
4.0409343	5f $^1F^{\circ}$ -4d $^1D$	0.009129	12	$0.347 \pm 0.087$
4.0490143	5g $^1G$ -4f $^1F^{\circ}$	0.07561	12	$4.32 \pm 0.117^d$
4.0490343	5g $^1G$ -4f $^1F^{\circ}$	0.02520	12	
4.052262	H I 5 $^{\circ}$ -4 $^{\circ}$		12	$78.0 \pm 1.47$
4.0545045	5d $^1D$ -4f $^1F^{\circ}$	$7.481E-5$	12	$<0.13$
4.0563459	5d $^1D$ -4f $^1F^{\circ}$	$2.012E-4$	12	$<0.13$
4.122730	5d $^1D$ -4p $^1P^{\circ}$	0.002223	13	$<1.01$
4.244067	5p $^1P^{\circ}$ -4d $^1D$	0.003122	No	
4.606601	5s $^1S$ -4p $^1P^{\circ}$	$7.479E-4$	No	
4.694980	5s $^1S$ -4p $^1P^{\circ}$	0.001581	No	

<sup>a</sup> With respect to He I 4473 Å line for Smits's  $N_e = 10^4$  cm $^{-3}$ ,  $T_e = 10^4$  K, case B.

<sup>b</sup> Number entries correspond to the bandpass observed.

<sup>c</sup> Uncertainties are 1  $\sigma$  and are statistical only. When the line is not detected, we use 3  $\sigma$  as the upper limit.

<sup>d</sup> This flux entry is the sum for these two blended lines (see text).

SWS02 scans provide the full resolution of the instrument (de Graauw et al. 1996). Observations used both the short wavelength (SW) and long wavelength (LW) sections of the simultaneous, dual bandpasses available. The total time observed was 12,633 s. Most of these data were taken for other purposes; here we present data as necessary for this paper. We covered H I Br $\alpha$  and eight of the 14 components of He I Br $\alpha$  with three separate bandpasses/bands: 6/1B, 12/1E, and 13/2A.<sup>6</sup> For all of the Br $\alpha$  lines discussed in this paper, the aperture was a rectangle 14"  $\times$  20". The orientation in the sky of the long axis

<sup>6</sup> We use the same numbering system used by the ISO Spectral Analysis Package (ISAP) to refer to our 35 bandpasses. Data here are from bandpasses 6, 12, and 13. ISAP is a joint development by the LWS and SWS Instrument Teams and Data Centers. Contributing institutes are CESR, IAS, IPAC, MPE, RAL, and SRON.

is at position angle 190°28'. The location of the center of the aperture is at  $\alpha$ ,  $\delta = (05^{\text{h}}35^{\text{m}}14^{\text{s}}.71, -05^{\circ}23'41''.5)$  (equinox J2000), 18"5 south and 26"2 west of  $\theta^1$  Ori C. This position was chosen to correspond to the center of other apertures used to observe with *Hubble Space Telescope*-FOS-1SW, a circular aperture of 0"86 diameter and GHRS-1SW, a 1"74 square aperture (see Fig. 1 in Rubin et al. 1997).

### 3.1. ISO Data Processing

The data products delivered to us underwent the standard pipeline (e.g., Leech et al. 1997, § 8) using the latest calibration files as of 1998 March 17. The detector signals marked in the pipeline as "bad data" were then automatically removed within ISAP; further removal of dubious data was also performed interactively with ISAP. The spectra of the 12 individual detectors in each observed bandpass were 3  $\sigma$ -clipped averaged first over scan direction and over all scans in the specific bandpass. We checked whether an application of a detector "flat-fielding" using the ISAP "Shift" routine (adjust all detectors to the mean signal level) would improve the consistency between the 12 detectors. However, this was found not to be the case here. Finally, an average over the detectors was performed. In all the averaging steps, a rebinning in wavelength was done using a bin size  $\sim 0.2\lambda/R$ , where  $R$  is the instrumental resolution at the particular wavelength (see Sturm 1997 for discussion of techniques used here). For bandpasses 6, 12, and 13, we used bin sizes of 0.0003, 0.0005, and 0.0005  $\mu\text{m}$ , respectively.

The ISAP routine Line Fit was used to fit a one- or two-component Gaussian to the detectable lines or to set an upper limit to the line flux when the line was not detected. Figure 1 displays the spectrum (bandpass 12) that contains most of the components of interest for this paper. Under all physical conditions expected for Orion, the dominant He I Br $\alpha$  feature is the blended triplet and singlet emission lines 5g  $^1G \rightarrow 4f^1F^{\circ}$  and 5g  $^1G \rightarrow 4f^1F^{\circ}$  at  $\lambda_{\text{vac}} = 4.0490143$  and 4.0490343  $\mu\text{m}$ . We use Martin (1987) for energy levels and S96 for line strength predictions. According to Smits's case B recombination theory, the line intensity of the triplet is 3 times the intensity of the singlet (for expected Orion physical conditions).

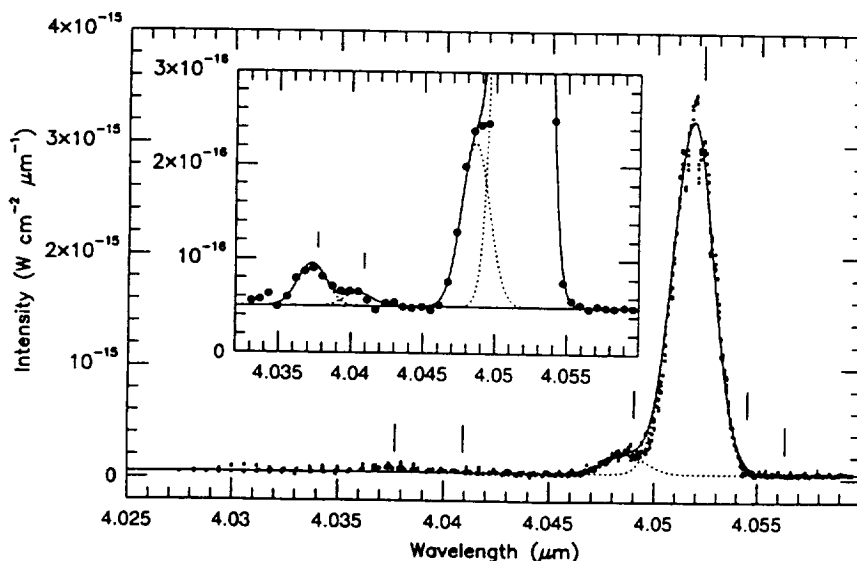


FIG. 1.—Portion of SWS bandpass 12 spectrum of the Orion Nebula observed with ISO. All line fits (dashed lines) are made with the final averaged data (see text) but are shown here superposed on all the data points used. The solid line is the sum of the Gaussian fits. Values of  $\lambda_{\text{vac}}$  for the H I and He I lines of interest are marked. The inset provides an expanded intensity scale; points here are the data averaged over scan direction and detectors.

If we thus weight the two blended components, the effective  $\lambda_{\text{vac}} = 4.0490193 \mu\text{m}$ . The difference  $\Delta\lambda$  from the H I Br $\alpha$  (at  $4.052262 \mu\text{m}$ ) is  $0.0032427 \mu\text{m}$ . In fitting the partially blended H I and He I lines, we use only one FWHM for both lines because the widths are clearly set by the instrumental FWHM. The best fit to the He I feature is obtained by fitting it alone using the portion that is unaffected by the much stronger H I line. The fit to these partially blended lines is shown in Figure 1, which also provides an expanded scale (inset). The measured flux for the blended pair of He I lines in Table 1 is  $4.32 \times 10^{-19} \text{ W cm}^{-2}$ . The line flux for the H I line is  $7.80 \times 10^{-18} \text{ W cm}^{-2}$ , the (instrumental) FWHM is  $0.00231 \mu\text{m}$ , and the  $\Delta\lambda$  of  $0.0032427 \mu\text{m}$  was fixed.

The next strongest He I line is clearly expected to be the  $5f^3F'' \rightarrow 4d^3D$  component at  $4.0377 \mu\text{m}$ , which also is measurable in bandpass 12. The weaker singlet  $5f^1F'' \rightarrow 4d^1D$  ( $4.0409 \mu\text{m}$ ) is also present. We fit each with a single Gaussian requiring the line centers to be fixed (to the observed H I center minus the known  $\Delta\lambda$ 's) and FWHMs to be fixed (to the H-line velocity FWHM). See Figure 1 and Table 1. The only other component of He I Br $\alpha$  that we detect is  $5p^3P'' \rightarrow 4s^3S$  at  $2.8550 \mu\text{m}$  in bandpass 6 (Fig. 2). We fit this with a Gaussian, fixing only the FWHM =  $0.00125 \mu\text{m}$ , provided by ISAP for band 1B. The central wavelength is  $2.8547 \pm 0.00008 \mu\text{m}$ . We can only set an upper limit on the  $5d^1D \rightarrow 4p^1P''$  at  $4.1227 \mu\text{m}$  component in bandpass 13. As we shall discuss, the  $4.1227 \mu\text{m}$  line may be expected to be somewhat brighter than the  $2.8550 \mu\text{m}$  line. However, the latter is observed for a much longer time and with more sensitive detectors (band 1B) compared with the  $4.12$  line (band 2A), resulting in a factor of  $\sim 25$  gain in detectability. The remaining two components of He I Br $\alpha$  are not detected. These are  $5d^1D \rightarrow 4f^1F''$  ( $4.0545 \mu\text{m}$ ) and  $5d^3D \rightarrow 4f^3F''$  ( $4.0563 \mu\text{m}$ ), covered by bandpass 12; we provide  $3\sigma$  upper limits for their line flux.

We use the data in Table 1 without correcting for extinction. In the smaller FOS-1SW aperture, we find that the extinction correction factors at  $2.855$  and  $4.052 \mu\text{m}$  are  $1.09$  and  $1.05$ , respectively. Thus, the maximum uncertainty in ratios of the He I components (ranging from  $2.855$ – $4.052 \mu\text{m}$ ) to H I Br $\alpha$  due to differential extinction is less than  $5\%$ . These extinction corrections are based on the observed *HST*/FOS data for Balmer, He I, and [O II] emission lines at position FOS-1SW. This set of corrections is consistent with the shape of the extinction curve derived from observations of the Orion Trapezium stars (Martin et al. 1998). A reddening map (O'Dell, Walter, & Dufour 1992) indicates no reason to expect a different conclusion for our larger ISO aperture.

#### 4. DISCUSSION AND CONCLUSIONS

The measurement of the H I and He I Br $\alpha$  components permits a new wavelength regime to be used to determine the He<sup>+</sup>/H<sup>+</sup> abundance ratio in Orion. We make the same assumptions that are generally made for deriving the He<sup>+</sup>/H<sup>+</sup> ratio from adjacent radio recombination lines of H I and He I. In particular, we assume that local thermodynamic equilibrium (LTE) holds for the population distribution in quantum number  $n$ . Then the departure coefficients ( $b_n$ -values), which measure departures from LTE, are unity. Even if there are departures, the non-LTE factors should be the same for both H and He and hence should not affect their ratio (e.g., Brown, Lockman, & Knapp 1978).

A very useful tool for interpreting our data in terms of a He<sup>+</sup>/H<sup>+</sup> abundance is S96 and more extensive tables kindly provided by D. P. Smits. These list theoretical strengths for the

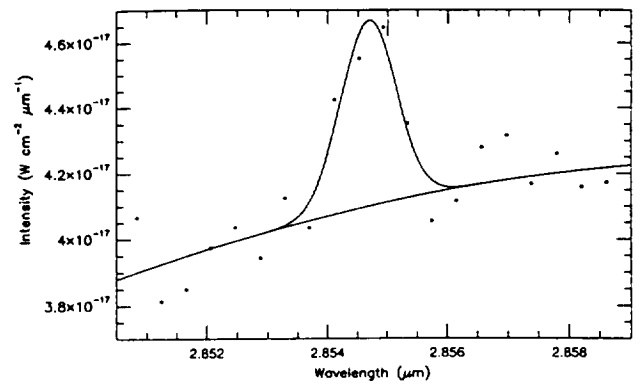


FIG. 2.—Portion of SWS bandpass 6 spectrum, showing the He I  $2.8550 \mu\text{m}$  line. We plot the Gaussian line fit with a quadratic continuum fit to the data, averaged over all four scans and over detectors.

He I lines for various values of  $N_e$  and  $T_e$ . We use the entries for  $N_e = 10^4 \text{ cm}^{-3}$  and  $T_e = 10^4 \text{ K}$  and case B (optically thick in the resonance lines), although we shall comment on how these change with other values. These are his tabulated values that are closest to the expected average values for  $N_e$  and  $T_e$  in Orion (Baldwin et al. 1991; Rubin et al. 1991). In Table 1, we list for the He I lines the intensity relative to the  $4473 \text{ \AA}$  line, as Smits has. The intensity of the blend of triplet and singlet (at  $4.0490 \mu\text{m}$ ), which is always the strongest feature in the He I Br $\alpha$  multiplet, is  $0.10081$ . This is  $0.65435$  of the intensity of the sum of all 14 lines in the multiplet. Let us use  $\text{frac}_{4.049}$  to represent this fraction. With the measured line flux of  $4.32 \times 10^{-19} \text{ W cm}^{-2}$ , the projected total for the multiplet is  $6.602 \times 10^{-19} \text{ W cm}^{-2}$ . The flux for the H I line is  $7.80 \times 10^{-18} \text{ W cm}^{-2}$ ; thus the He I/H I line ratio is  $0.0846 \pm 0.0028$  (only the flux uncertainties have been propagated). This may be interpreted as equivalent to the He<sup>+</sup>/H<sup>+</sup> ratio along the specific observed rectangular column through the nebula. It is not in general equal to the He/H abundance ratio unless the He<sup>+</sup> and H<sup>+</sup> ionization structure are the same (e.g., see Rubin 1969).

The value of  $\text{frac}_{4.049}$  changes somewhat when different  $N_e$ ,  $T_e$  pairs are considered. Smits has calculated these for  $N_e = 100, 10^4$ , and  $10^6 \text{ cm}^{-3}$  and for  $T_e = 20,000, 10,000, 5000 \text{ K}$  and lower (continuing by factors of 2). For expected Orion conditions, the variation in  $\text{frac}_{4.049}$  is slight. Over the full range that we have explored,  $\text{frac}_{4.049}$  varies by only  $9\%$  from a low of  $0.64592$  ( $N_e = 10^6, T_e = 10^4$ ) to a high of  $0.70472$  ( $N_e = 100, T_e = 5000$ ).

Following the above notation, we examine the variation with  $N_e$  and  $T_e$  of the fractions of the total He I multiplet in some of the other key (or measured) lines:  $\text{frac}_{4.0377}$ ,  $\text{frac}_{4.0409}$ , and  $\text{frac}_{2.855}$ . The intensity of the  $4.0409$  line is essentially always a factor of 3 weaker than that of  $4.0377$  over our range of interest (case B, S96). Thus, we need comment on only the  $2.855$  and  $4.0377$  lines. For  $N_e = 10^4 \text{ cm}^{-3}$ ,  $T_e = 10^4 \text{ K}$  (case B),  $\text{frac}_{4.0377} = 0.17779$  and  $\text{frac}_{2.855} = 0.011126$ . Over the full range that we have explored,  $\text{frac}_{4.0377}$  varies by a factor of  $1.105$  from  $0.16435$  ( $N_e = 100, T_e = 5000$ ) to  $0.18163$  ( $N_e = 10^6, T_e = 10^4$ ), and  $\text{frac}_{2.855}$  varies by a factor of  $1.605$  from  $0.0072331$  ( $N_e = 100, T_e = 5000$ ) to  $0.011606$  ( $N_e = 10^6, T_e = 10^4$ ).

The variation in both of these fractions is *opposite* to that of  $\text{frac}_{4.049}$  in that lower  $T_e$  and lower  $N_e$  result in lower values. The small variation of  $\text{frac}_{4.0377}$  depends on changes in both

$T_e$  and  $N_e$ . However, the more substantial variation of  $\text{frac}_{2.855}$  depends much more sensitively on changes in  $T_e$  rather than  $N_e$ . As such, one could envision using the flux ratio of the 2.855 line to the 4.049  $\mu\text{m}$  line as a way to measure  $T_e$ . This ratio is predicted to vary by a factor of 1.75 from 0.010264 ( $N_e = 100$ ,  $T_e = 5000$ ) to a high of 0.01797 ( $N_e = 10^6$ ,  $T_e = 10^4$ ).

Smits (1996) has also calculated the relative emissivities for the He I singlets for case A (optically thin in the resonance lines). When we use these values instead of case B, there is very little difference in any of the  $\text{frac}_\lambda$  values mentioned here; for instance, at  $N_e = 10^4 \text{ cm}^{-3}$  and  $T_e = 10^4 \text{ K}$ , changes are  $\leq 1.5\%$ . Thus, our further discussion will proceed with case B.

From Table 1, the observed flux ratio  $F(4.0377)/F(4.0490) = 0.257$ . This ratio is in the range of the theoretical tabular values; it is a factor of only 1.057 less than expected for  $N_e = 10^4$ ,  $T_e = 10^4 \text{ K}$ . This close agreement is tempered by the uncertainty in the line measurements. Because the S/N is much worse for the 4.0377 line than for the 4.0490 feature, we do not use it in our abundance analysis.

The ratio of the flux in the weak He I 2.855  $\mu\text{m}$  line to the flux in the 4.0490  $\mu\text{m}$  blend permits an assessment of  $T_e$  in the He<sup>+</sup> region. The predicted ratio increases monotonically with  $T_e$ ; it is 0.010718, 0.017002, and 0.027048 at 5000, 10,000, and 20,000 K, respectively (using  $N_e = 10^4 \text{ cm}^{-3}$ ). In this  $T_e$  range, which applies to most H II regions and planetary nebulae, the flux ratio is roughly  $\propto T_e$ . Thus a measurement of this ratio appears to be a promising gauge for planetary nebulae as well. From our measured ratio, 0.01665,  $T_e \sim 9700 \text{ K}$ . Although the  $T_e$  value could be more tightly constrained with a finer  $T_e$  grid than provided now by S96, the uncertainties in the 2.855 flux make that somewhat academic.

We compare with other He<sup>+</sup>/H<sup>+</sup> radio and optical determinations. Invariably, these will have been made centered at other positions in the Orion Nebula and with different size apertures. The radio results include  $0.091 \pm 0.005$  (66 $\alpha$  line at 22 GHz with beam FWHM = 0.7) (Thum, Mezger, & Pankonin 1980). Lockman & Brown (1982) found  $0.082 \pm 0.008$  (76 $\alpha$ , 10.5 GHz, 3.2) and  $0.088 \pm 0.006$  (95 $\beta$ , 14.7 GHz, 2.2) for the central lines of sight. They concluded from a review of the Orion data available then that there was no correlation of He<sup>+</sup>/H<sup>+</sup> with  $n$ . Peimbert et al. (1992) found the same result within their uncertainties by observing three line pairs with frequencies  $\sim 8.6 \text{ GHz}$  using the same telescope/receiver (FWHM = 3.2):  $0.0921 \pm 0.0025$  (91 $\alpha$ ),  $0.0839 \pm 0.0052$  (114 $\beta$ ), and  $0.1049 \pm 0.0080$  (130 $\gamma$ ).

There is much optical data for Orion, but observations are of considerably more limited spatial coverage compared with the radio beams. We summarize the results of two recent studies. From their extensive He I data, Osterbrock et al. (1992) found He<sup>+</sup>/H<sup>+</sup> = 0.0894, and correcting for neutral He,

He/H = 0.101. Esteban et al. (1998) did echelle spectrophotometry at two positions. Their final mean values for He<sup>+</sup>/H<sup>+</sup> are  $0.0856 \pm 0.0069$  and  $0.0893 \pm 0.0092$ ; their total He/H = 0.0977. We conclude that the He<sup>+</sup>/H<sup>+</sup> result of 0.085 from this study is typical of the values found by others. There is no observationally driven imperative here that would indicate a departure from the Smits theory. The combined observational/theoretical picture points to the He<sup>+</sup> volume being smaller than the H<sup>+</sup> volume. In their "blister" model for Orion, Rubin et al. (1991) calculated a flux ratio of He I to H I radio recombination lines  $\sim 0.083$  for the central lines of sight when convolved with Gaussian beams up to FWHM  $\sim 1'$ . This resulted when the total He/H was 0.1. The total He/H ratio for Orion is higher than the He<sup>+</sup>/H<sup>+</sup> ratio, with the difference being attributed to some neutral helium in the H II region.

ISO will provide a rich pool of H I and He I lines in nebulae, many with  $\Delta n \geq 2$ . Of all those accessible, Br $\alpha$  is probably the easiest to use to measure the adjacent pair. It is the brightest and has the largest relative separations between their line centers. For instance, at Pf $\alpha$ , the wavelength difference between H I and the strongest expected He I component ( $6h \text{ } ^3H'' \rightarrow 5g \text{ } ^3G$ ) is 0.003721  $\mu\text{m}$ . Thus  $\lambda/\Delta\lambda = 2000$ , which exceeds the range in SWS resolution,  $R \sim 1000\text{--}1500$ , and leads to unresolved lines. This contrasts with  $\lambda/\Delta\lambda \sim 1250$  for the strongest Br $\alpha$  lines, while  $R$  ( $\sim 1300\text{--}2100$ ) at this wavelength is sufficient to resolve these components for the most part (Leech et al. 1997, p. 64). Furthermore, the H I Pf $\alpha$  intensity should be about one-third that of Br $\alpha$ . Already for Pf $\alpha$ , the brightest He I component shows only as a slight asymmetry on the blue wing of the stronger H I line. Indeed, many IR measurements of a H I line are likely to also include one or more significant He I line contributions. By attributing all the flux to the H I line, one will underestimate abundance ratios relative to H<sup>+</sup>. This has usually not been taken into account in the past when deriving abundances of other ions/elements relative to H. In addition, errors in the velocity and line width may be introduced by failure to account for and to correct for the blended He line. Because the strongest He I lines will generally be on the blue side of their counterpart H I line, interpreting a blended feature as only H I will cause a spurious bias to lower velocities. In the present case, had the 4.049 He I Br $\alpha$  feature remained unresolved from the H I line,  $V_{\text{helio}}$  attributed to the H I line would be 12  $\text{km s}^{-1}$  too small.

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